REPORT DOCUMENTATION PAGE

AFRL-SR-BL-TR-00-

0636

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	August 2000	Final, July 1, 1997 to May 31, 2000

4. TITLE AND SUBTITLE

Vector-Sensor Algorithms for Source Tracking and Jam-Free Naviation

5. FUNDING NUMBERS

F49620-97-1-0481

6. AUTHOR(S)

Dr. Arye Nehorai

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Electrical Engineering and Computer Science (M/C 154)
The University of Illinois at Chicago
851 South Morgan Street, Room 1120 SEO
Chicago, Illinois 60607-7053

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Office of Scientific Research
AFOSR/NM
801 North Randolph Street Room 732
Arlington, VA, 22203-1977

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION / AVAILABILITY STATEMENT

Distribution Unlimited

20001127 024

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 Words)*

We obtained the following results, according to research areas. Performance Bounds: Gene al bounds on the mean-square errors for discrete-time nonlinear filtering and for estimating general vector sys' ems.

EM arrays: Methods for target tracking, direction estimation, and interference cancellation, with passive EM vector sensors; detecting the wake of a ship using an airborne SQUID magnetic transducer; estimating range, velocity, and direction with active radar array; equalizing and estimating channels with communication antenna arrays in spatially correlated noise.

Acoustic arrays: Beamforming using acoustic vector sensors (AVS's); fast wideband algorithms for locating airborne targets using a passive distributed array of AVS's; direction finding with an AVS array near a reflecting boundary; analysis of cross-correlations between wide-band noise components of an AVS.

Chemical arrays: Methods for automatic environmental monitoring and land-mine detection and localization using chemical sensor arrays.

Biomedicine: Estimating evoked dipole responses, and tracking a dynamic source with EEG/MEG sensor arrays; estimating mechanical properties of the heart using tagged-MRI; adaptive hearing aids.

14. SUBJECT TERMS	15. NUMBER OF PAGES
EM/acoustic vector sensors, array processing, radar, communications, performance bounds.	19
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL

16 Oct 00
accept [illegible]

Final Report
Research Under Grant AFOSR-F49620-97-0481
July 1, 1997 to May 31, 2000

Arye Nehorai
EECS Department
The University of Illinois at Chicago
http://www.eecs.uic.edu/~nehorai/

August 24, 2000

Advanced-Sensor Signal Processing:

Over the last several years, we have introduced the use of several advanced sensors to signal processing. By incorporating novel sensor technologies and measurement models that make full use of the physical information available, we have added a new dimension to signal processing and considerably enhanced its practical utility. In recognition to our leadership and contribution in this area, we have invited to present a summary of this work in [1].

General Performance Bounds:

In [2] we derived a mean-square error lower bound for the discrete-time nonlinear filtering problem, based on the Van Trees' (posterior) version of the Cramér-Rao inequality. This lower bound is applicable to multidimensional nonlinear, possibly non-Gaussian, dynamical systems and is more general than the previous bounds in the literature. The case of a singular conditional distribution for the one step ahead state vector given the present state was considered. The bound was evaluated for three important examples: recursive estimation of slowly varying parameters of an autoregressive process, tracking a slowly varying frequency of a single cisoid in noise, and tracking the parameters of a sinusoidal frequency with sinusoidal phase modulation.

In [3], [4] we proposed a unified framework for the analysis of estimators of geometrical vector quantities and vector systems, through a collection of performance measures. Unlike standard performance indicators, these measures have intuitive geometrical and physical interpretations, are independent of the coordinate reference frame, and are applicable to arbitrary parameterizations of the unknown vector or system of vectors. For each measure we derived both finite-sample and asymptotic lower bounds that hold for large classes of estimators and serve as benchmarks for the assessment of estimation algorithms. Like the performance measures themselves, these bounds are independent of the reference coordinate frame and we discussed their use as system design criteria.

Electromagnetic Array Processing for Radar and Communications:

Our main original results on electromagnetic vector-sensor processing have appeared in a book chapter [5]. We introduced the concept of EM *vector sensors*, which measure the complete EM field at a single point, to the signal processing community. Such sensors are now commercially available. Using these sensors, we created methods for estimating the directions of arrival and polarization states of electromagnetic waves. To analyze their performance, we defined quality measures for estimating direction and orientation in 3D space, including mean-square angular error and covariance of vector-angular error, and derived lower bounds on them. These quality measures and bounds are not limited to EM waves and are already used by researchers in various fields. We conducted identifiability analyses that showed that with one vector sensor it is possible to find the directions and polarization ellipses of up to 3 sources. Thus, we determined that with one vector sensor it is possible to do what historically was done by an array of distributed scalar sensors. Furthermore, we showed that a vector sensor can resolve co-incident and very closely spaced sources based on polarization differences. This can be of considerable benefit. For example, in cellular communications it provides a new multiple access diversity mechanism for increasing base station capacity. We also proposed a very fast algorithm for finding the source direction and analyzed its asymptotic statistical performance. A patent has been awarded for this algorithm.

In [6] we developed two high-resolution methods for direction-of-arrival estimation with electromagnetic vector sensors. Both methods, of which the first is ESPRIT-based and the second MUSIC-based, are applicable to scenarios where completely polarized and incompletely polarized signals co-exist. The ESPRIT-based method is computationally efficient, but there must be three vector sensors with a specific sensor arrangement in order to apply the method. On the other hand, the MUSIC-based method, although involving more computations, can work without the constraint that the ESPRIT-based method faces. In addition, neither method requires *a priori* information regarding the numbers of completely polarized and incompletely polarized signals impinging on the array, and will inherently provide such information.

We developed in [7]-[9] a beamformer employing a single electromagnetic vector sensor. This beamformer is of minimum-noise-variance type, and is used for interference rejection. It creates a beam focused in both direction and polarization that minimizes interference from undesired sources (e.g. jammers). In this way it can do the work of multiple scalar polarization-selective sensors.

We considered two types of signals: one carries a single message, and the other carries two independent messages simultaneously. The state of polarization of the interferences under consideration ranged from completely polarized to unpolarized. To analyze the performance, we first obtained explicit expressions for the signal to interference-plus-noise ratio (SINR) in terms of the parameters of the desired signal, interference, and noise. Then we discussed some physical implications associated with the SINR expressions. Our SINR results provide a basis for effective interference suppression, as well as generation of dual-message signals in which there is minimum crosstalk.

The key advantages of our beamformer over current systems are that it:

- Works in three dimensions using only a single vector sensor, significantly simplifying receiver design and occupying very little space. Most current methods require a two-dimensional array to implement three-dimensional focusing.
- Exploits any polarization properties that the incoming signal may have. This provides a crucial criterion for distinguishing and isolating signals that may otherwise overlap too much for conventional systems.
- Extends easily to multiple sources with diverse carrier frequencies and polarizations, using multiple vector sensors as receivers.
- Distinguishes between sources without ambiguities, since it searches in both the polarization and direction domains. Existing methods suffer from frequency/localization ambiguities as they use only time delay information.

Numerical examples confirmed our analytical results.

In [10] we extended previous work to the space-time-polarization domain and applied vector sensor array processing to estimate the angles-of-arrival(AOAs) and delays of multipath channels. A MUSIC like algorithm for joint angle and delay estimation with a vector sensor array was derived. Simulation results showed that the space-time-polarization parameterization of the multipath channels can result in better accuracy and resolution performance.

In [11], [12] we presented two adaptive cross-product algorithms for tracking the direction to a moving source using an electromagnetic vector sensor. The first was a cross-product algorithm with a forgetting factor, for which we analyzed the performance and derived an asymptotic expression of the variance of angular estimation error. We found the optimal forgetting factor that minimizes this variance. The second was a Kalman filter combined with the cross-product algorithm, which is applicable when the angular acceleration of the source is approximately constant.

In [13], [14] we proposed an approach to localize multiple sources based on spatially distributed electric and magnetic component sensors. By jointly exploiting all available electromagnetic information as well as spatial diversity (time delays), this approach should outperform both a single vector-sensor and scalar-sensor arrays in accuracy of direction of arrival estimation.

In [15], [16], we derived Cramér-Rao bound (CRB) expressions for the range (time delay), velocity (Doppler shift), and direction of a point target using an active radar or sonar array. First, general CRB expressions were derived for an arbitrary signal waveform and a noise model that allows both spatial and temporal correlation. We discussed the relationship between the CRB and ambiguity function for this model. Then we specialized our CRB results to temporally uncorrelated noise and the practically important signal shape of a linear frequency modulated (chirp) pulse sequence. We computed the CRB for a 3-dimensional array with isotropic sensors in spatially uncorrelated noise and showed that it is a function of the array geometry only through the "moments of inertia" of the array. The volume of the confidence region for the target's location was proposed as a measure of accuracy. For this measure, we showed that the highest (and lowest) target location accuracy is achieved if the target lies along one of the principal axes of inertia of the array. Finally, we compared the location accuracies of several array geometries. For temporally uncorrelated noise and unknown spatially correlated noise, we presented in [17] maximum likelihood (ML) methods for active estimation of the time delay, Doppler shift, and direction.

In [18], [19] we addressed the problem of identifying and equalizing communication channels in the presence of strong co-channel interference (CCI). We considered the interference and noise as colored noise of unknown covariance and exploited the underlying structure and constraints of the transmitted data and channel outputs. The proposed algorithm optimizes a weighted least-squares cost function using an iterative reweighting alternating minimization procedure. Numerical examples were presented and showed that the proposed algorithm is capable of achieving reliable channel identification and equalization in the presence of strong CCI at moderate SNR.

In [20] we proposed a new approach to joint estimation of directions and arrival times of for multipath channels parameterized by a finite number of path gains, direction and time of arrivals. The proposed approach exploits *a priori* knowledge of the pulse shaping filters and array manifold. The significance of this approach is that the directions of arrival (DOA) and times of arrival (TOA) of the multipath signals can be estimated directly from the oversampled channel outputs without assuming channel stationarity over the time-slot, nor requiring a start-up sequence in each time-slot to obtain estimates of the channel.

We presented in [21], [22] ML methods for space-time fading channel estimation with an antenna array in spatially correlated noise having unknown covariance. The received signal was modeled as a linear combination of multipath-delayed and Doppler-shifted copies of the transmitted waveform. We considered structured and unstructured array response models, and derived the CRB for the unknown directions of arrival, time delays and Doppler shifts. We also proposed coherent matched-filter and concentrated-likelihood receivers which account for the spatial noise covariance.

In [23], [24] we introduced methods for detecting the wake of a ship using an airborne SQUID magnetic transducer. Wake induced by motion of vessels may extend for tens of kilometers and exist for hours under certain conditions in open sea. This forms a useful feature for long-range ship detection. Our methods are applicable for passively detecting a ship wake using measurements obtained by an airborne SQUID magnetic transducer that measures the first-order gradients of the magnetic signature induced by the wake. Analytical formulas of wake magnetic gradients were derived to provide guidelines for the airborne detectors. We also derived probability bounds of wake detection for cross-correlation and square-law detectors, which are useful to predict the expected performance.

Acoustic Array Processing:

In [25] we considered the use of arrays of acoustic vector sensors for underwater direction-of-arrival estimation. Acoustic vector sensors measure the acoustic pressure and all three components of acoustic particle velocity at a single point. They provide enhanced performance over traditional pressure-sensor arrays, allowing the use of smaller apertures, and full bearing resolution with simple linear geometries. We conducted a detailed analysis of their optimum performance, in terms of the Cramer-Rao bound, for a single source. As a result we identified two distinct phenomena that account for their improved performance over standard systems: (i) an effective increase in signal-to-noise ratio (SNR) due to extra measurements of the inter-sensor phase shifts and (ii) extra independent bearing information arising from direct measurement of the velocity field's structure. By examining these phenomena separately, we determined conditions on the array's size, shape, and SNR, under which the use of vector sensors is most advantageous, and quantified that advantage.

We also extended beamforming and Capon direction estimation procedures for use with vector-sensor arrays. We showed that the extra velocity-field information removes all ambiguities such as grating lobes. This allows the use of simple structures for which fast direction estimation algorithms exist, e.g. a uniform linear array (ULA), to determine both the azimuth and elevation of a source (a conventional ULA can only determine conic angle). It also means that spatially undersampled arrays of vector sensors can be used to increase aperture and hence performance. Finally we derived large-sample approximations for the mean-square errors of these two estimators.

In [26] we carefully considered the effect of sensor placement on the direction-of-arrival estimation performance of an array of acoustic vector sensors. We derived expressions for the Cramer-Rao bound on the azimuth and elevation of a single source, for an array of arbitrary shape. Using this result, we found necessary and sufficient conditions on the geometry to ensure that the ability to estimate one of the bearing parameters is independent of knowledge of the other. We argued that these conditions provide a compelling criterion for array-shape design. We then considered a bound on the mean-square angular error, which is a very useful single measure of performance in three-dimensional bearing problems. Using this bound, we extended our previous conditions to provide a sufficient set of conditions that ensure the array's optimal performance is isotropic. We also determined that knowledge of the signal and noise powers makes no difference to the optimal ability to estimate the bearing.

In [27] we considered the passive direction-of-arrival (DOA) estimation problem using arrays of acoustic vector sensors located in a fluid, at or near a reflecting boundary. We formulated a general measurement model applicable to any planar surface, derived an expression for the Cramér-Rao bound (CRB) on the azimuth and elevation of a single source, and obtained a bound on the mean-square angular error (MSAE). We then examined two applications of great practical interest: hull-mounted and seabed arrays. For the former, we used three models for the hull: an ideal rigid surface for high frequency, an ideal pressure-release surface for low frequency, and a more complex, realistic layered model. For the seabed scenario we modeled the ocean floor as an absorptive liquid layer. For each application we used the CRB, MSAE bound, and beampatterns to quantify the advantages of using velocity and/or vector sensors instead of pressure sensors. For the hull-mounted application, we showed that normal component velocity sensors overcome the well-known, low-frequency problem of small pressure signals without the need for an undesirable "stand-off" distance. For the seabed scenario, we also derived a fast wideband estimator of the source location using a single vector sensor.

Most array processing methods require knowledge of the correlation structure of the noise. While such information may sometimes be obtained from measurements made when no sources are present, this may not always be possible. Furthermore, measurements made *in-situ* can hardly be used to analyze system performance before deployment. The development of models of the correlation structure under various environmental assumptions is therefore very important. In [28] we obtained integral and closed form expressions for the auto- and cross-correlations between the components of an acoustic vector sensor (AVS) for a wideband noise field, under the following assumptions concerning its spatial distribution: (i) azimuthal independence; (ii) azimuthal independence and elevational symmetry, and (iii) spherical isotropy. We also derived expressions for the cross-covariances between all components of two spatially displaced AVS's in a narrowband noise field under the same assumptions. These results can be used to determine the noise covariance matrix of an array of acoustic vector sensors in ambient noise. We applied them to a uniform linear AVS array to asses its beamforming capabilities and localization accuracy, via the Cramér-Rao bound, in isotropic and anisotropic noise.

In [29], [30], and [31], we derived fast wideband algorithms for determining the bearing and 3-D position of a target using a distributed array of acoustic vector sensors (AVS's) situated in freespace or on a reflecting boundary. Each AVS locally estimates the bearing from its location to the target using a rapid wideband estimator we developed based on the acoustic intensity vector; adaptations of beamforming-based bearing estimators were also discussed. The local bearing estimates are then transmitted to a central processor where they are combined to determine the 3-D position. Closed-form weighted least-squares (WLS) and reweighted least-squares algorithms were proposed to achieve this. A bound on the mean-square angular error of the local bearing estimates was obtained, and used along with the data to adaptively determine the weights for the WLS routine. In addition a measure of potential 3-D location performance for the distributed system was developed based a two stage application of the Cramér-Rao bound. The results are relevant to the localization of underwater and airborne sources using freely-drifting, seabed, and ground sensors. Numerical simulations were used to illustrate the results.

We have graduated Malcolm Hawkes whose work on acoustic-vector sensor processing is summarized in his PhD thesis [32].

In [33] we propose an FFT based algorithm for implementing adaptive directionality of dual microphone application systems such as hearing aids, etc. We show theoretically and by simulation results that the proposed scheme can provide an adaptive and effective reduction of the noise that is in different direction from the one of the target signal. Wealso discuss in more details this proposed scheme from the practical application and hardware implementation points of view. In comparison with other available methods, the proposed scheme has the following advantages. It provides: 1. a simple and realizable implementation structure; 2. the elimination of an additional delay processing unit for endfire orientation microphones; 3. an effective solution of microphone mismatch problem and 4. the elimination of the assumption that the target signal must be exactly straight ahead. With these features, this proposed scheme could provide a new tool to implement adaptive directionality in related application fields.

Chemical Array Processing for Environmental Monitoring:

In [34], [35] we developed methods for automatic environmental monitoring of disposal sites on the deep ocean floor using chemical sensor arrays and statistical hypothesis testing. Such sites have been proposed for the relocation of waste materials dredged from harbors and shipping channels (for more details see the transitions section below). We modeled the transport of pollutants as a diffusion process and derived the associated concentration distribution. To derive the measurement and statistical models we exploited the spatial and temporal evolution of the concentration distribution. We proposed two detectors, the generalized likelihood ratio (GLR) test and the mean detector. The GLR detector gives a higher performance and is applicable when the physical model is reliable, while the mean detector is useful when a precise model is not available. To analyze the performance of both detectors we derived expressions for the probabilities of detection and false alarm. We then proposed several algorithms for the design of chemical sensor arrays satisfying criteria specified in terms of these probabilities, as well as optimal selection of number of sensors and time samples. To illustrate the applicability of our results we determined the optimal arrays for various set of model parameters and design criteria.

In [36], [37] we developed methods for automatic detection and localization of landmines using chemical sensor arrays and statistical signal processing techniques. The transport of explosive vapors emanating from buried landmines was modeled as a diffusion process in a two-layered system consisting of ground and air. The measurement and statistical models were then obtained from the associated concentration distribution. We derived two detectors, the generalized likelihood ratio (GLR) test and the mean detector, and determined their performance in terms of the probabilities of false alarm and detection. To determine the unknown location of a landmine we derived a maximum likelihood (ML) estimation algorithm and evaluate its performance by computing the Cramer-Rao bound. The results were applied to the design of chemical sensor arrays, satisfying criteria specified in terms of detection and estimation performance measures, and for optimally selecting the number and positions of sensors and the number of time samples. To illustrate the potential of the proposed techniques in a realistic demining scenario, we derived a moving-sensor algorithm, in which the stationary sensor array is replaced by a single moving sensor. Numerical examples were given to demonstrate the applicability of our results.

EEG/MEG Array Processing:

In [38]-[40] we developed maximum likelihood (ML) methods for estimating evoked dipole responses with electroencephalography (EEG) and magnetoencephalography (MEG) sensor arrays, which allow for spatially correlated noise between sensors with unknown covariance. The electric source was modeled as a collection of current dipoles at fixed locations and the head as a spherical conductor. The dipoles' moments were permitted to vary with time as linear combinations of parametric or non-parametric basis functions. We estimated the dipoles' locations and moments, and derived the Cramér-Rao bound for the unknown parameters. We also proposed an ML-based method for scanning the brain response data, which can be used to initialize the multi-dimensional search required to obtain the true dipole location estimates. We showed that the derived ML estimates are asymptotically more efficient than the commonly used nonlinear least square estimates by showing that the difference in their asymptotic variances is negative semidefinite. We introduced a goodness-of-fit measure accounting for multiple time snapshots and correlated noise. Numerical examples with both simulated and experimental data were presented to demonstrate the performance of the proposed method.

In [41] we further discussed the case when the dipoles have fixed orientations in time. We estimated the dipoles' locations and moments, and derive the Fisher information matrix for the unknown parameters. We also proposed an array optimization criterion based on minimizing the volume of the linearized confidence region.

In [42] we derived a generalized least squares (GLS) method for estimating propagating dipole sources using EEG and MEG sensor arrays. The dipole locations varied in time according to a parametric model, whereas their moments varied arbitrarily from one time point to another. We also derived the Cramér-Rao bound for the trajectory parameters. We then extended the above method to account for unknown spatially correlated noise. This method has potential applicability for epilepsy patients.

In [43]-[45] we derived Cramér-Rao bounds on the errors of estimating a single dipole's location and moment using EEG, MEG and combined EEG/MEG modality. We used realistic head models based on knowledge of surfaces separating tissues of different conductivities, obtained from magnetic resonance (MR) or computer tomography (CT) imaging systems.

The electric potentials and magnetic field components at the respective sensors were obtained as functions of the source parameters through integral equations. These equations were formulated for solution by the boundary or the finite element method (BEM or FEM), with a weighted residuals technique. We presented a unified framework for the measurements computed by these methods that enables the derivation of the bounds. The resulting bounds may be used, for instance, to construct the confidence regions in dipole localization, and to choose the best configuration of sensors for a given patient and region of expected source location. Numerical results demonstrated an application for showing regions of good and poor expected accuracy in estimating the source parameters, based on a real EEG/MEG system.

In [46]–[47] we analyzed fundamental limitations in estimating the position, orientation and intensity of dynamic brain sources with data from (EEG/MEG). We derive the Cramer-Rao lower bound on the covariance of the estimated parameters of a dynamic dipole source. Our results extended previous work on parameter estimation of a fixed brain source through computing the CRB for nonlinear dynamical source models.

Estimating Mechanical Properties of the Heart Using MRI:

We presented in [48], [49] a new method for determining material properties of the myocardium. Changes in these properties can cause certain cardiac dysfunctions such as heart failure, ischemic heart disease, etc. Such changes can pre-date these dysfunctions and so serve as an early indicator of heart disease. We developed a model to relate the strain at various locations during the whole heart cycle to the material parameters, which are then estimated by minimizing a distance measure between the predicted strain and strain measurements obtained from tagged MRI images. Our approach combines a finite-element formulation and dynamic modeling, followed by a nonlinear least-squares optimization. We based our model on the material's stiffness tensor of anisotropic and non-homogeneous myocardium, so eliminating assumptions needed for the existence of a strain energy potential required in the standard approach. By exploiting the dynamics of heart-wall motion we achieved better performance in terms of estimation error.

Transitions:

Our analytical results on performance for radar sensor arrays in [16], [17] are applied to the TechSat21 system. TechSat21, in general, is a radar system using an array of microsatellites. [See http://www.vs.afrl.af.mil/VSD/TechSat21/]. The purpose is to estimate direction, range, and velocity of a ground moving target. Our results are used to predict the performance of this system (e.g. accuracy of estimating the above target parameters in terms of Cramer-Rao bounds and ambiguity functions) and optimally design its configuration. We are also exploring the use of our ideas of vector sensors, which should give a great benefit of removing ambiguities (grating lobes) in direction finding. This work is done in collaboration with Dr. John Garnham [Phillips Laboratory, VTRA, telephone: (505) 846-7224], who provides us with the numerical data for this system.

Our idea of acoustic vector-sensor processing is being pursued by researchers at NUWC in Newport and by the NAVY ASTO (advanced systems and technology) office. Our results are applied to locate sources with high accuracy using a small-size acoustic sensor array. The researchers at NUWC are exploring the potential advantage of acoustic vector sensors for use in hull-mounted applications, in particular conformal submarine bow-dome arrays. They are conducting experiments to confirm our analytical results. We are collaborating with them on the analysis and simulation of specific scenarios, and provide them with coded algorithms for the processing of their raw measurements and integration into the experimental hardware and act as consultants. The first and second stages of this project were successfully concluded with demonstrations of our techniques in a water tank in December 1998 and July 2000. The researchers at NUWC are now moving to the third round of experiments that will take place in a lake, and in which we shall again be involved. The project will then move to final experimental stage involving sensors mounted on a sea going vessel. ASTO has recently transitioned the research from category 6.1 to categories 6.2, 6.3 and 6.4. It has also created a working group of people from academia and industry to further develop and investigate the use of the new concept for hull-mounted velocity sensors. The NUWC project is headed by Dr. Ben Cray [NUWC, Newport, telephone 401-841-7505 ext. 38454]. The ASTO project is headed by Commander John Polcari and Mr. Mike Traweek [PEO(USW) ASTO G-4, Undersea Warfare, telephone: (703) 604-6013 ext. 527].

Our results on chemical sensor array processing have been pursued by DARPA and NRL's Stennis Space Center to design procedures for environmental monitoring of disposal sites. The annual buildup of sediment in U.S. ports and harbors must be removed in order to avoid detrimental effects to U.S. Naval operations and maritime trade. It has been proposed to relocate the dredged material in new disposal sites in the abyssal ocean. Since the dredged material may contain pollutants and toxins, environmental and political concerns dictate that monitoring of pollutants near the disposal sites be performed. DARPA and NRL has awarded us and a group of researchers 6.3 grants to develop techniques for automatic detection of pollutants at deep ocean relocation (DOR) sites on the abyssal sea floor, using a distributed co-operative chemical sensor array. These grants were a transition from our original research. The sponsors of this grant were Dr. Philip Valent [telephone 601-688-4650] and Dr. David Young [telephone 601-688-5507].

References

[1] A. Nehorai "Advanced-Sensor Signal Processing," (part of "Highlights of Statistical Signal and Sensor Array Processing," *IEEE Signal Processing Magazine,* Vol. 15, pp. 43-45, Sept. 1998. (Invited, for the 50th Anniversary of the IEEE SP Society.)

[2] P. Tichavský, C. Muravchik, and A. Nehorai, "Posterior Cramér-Rao Bounds for Adaptive Discrete-Time System Identification," *IEEE Trans. on Signal Processing,* pp. 1386-1396, Vol. SP-46, May 1998.

[3] A. Nehorai and M. Hawkes, "Performance Measures for Estimating Vector Systems," *IEEE Int. Conf. Acoust., Speech, Signal Processing,* pp. 1829-1832, Phoenix, AZ, March 1999.

[4] A. Nehorai and M. Hawkes, "Performance Bounds for Estimating Vector Systems," *IEEE Trans. on Signal Processing,* pp. 1737-1749, Vol. SP-48, June 2000.

[5] A. Nehorai and E. Paldi, "Electromagnetic Vector-Sensor Array Processing," in *Digital Signal Processing Handbook,* V. Madisetti and D. Williams, eds., pp. 65.1-65.26, CRC Press, 1998.

[6] K-C. Ho, K-C. Tan, and A. Nehorai, "Estimating Directions of Arrival of Completely and Incompletely Polarized Signals with Electromagnetic Vector Sensors," *IEEE Trans. on Signal Processing,* Vol. SP-47, pp.2845-2852, Oct. 1999.

[7] A. Nehorai, K.-C. Ho, and B. T. G. Tan, "Minimum-Noise-Variance Beamformer with an Electromagnetic Vector Sensor," *IEEE Int. Conf. Acoust., Speech, Signal Processing,* pp. 2021-2024, Seattle, WA, May 1998.

[8] A. Nehorai, K.-C. Ho, and B.T.G. Tan, "Minimum-Noise-Variance Beamformer with an Electromagnetic Vector Sensor," *IEEE Trans. Signal Processing,* Vol. SP-47, pp. 601-618, Mar. 1999.

[9] A. Nehorai, K.-C. Ho, and B. Tan, "Electromagnetic Vector Sensors with Beamforming Applications," to appear in *Handbook on Antennas in Wireless Communications,* L. Godara, ed., CRC Press, 2001.

[10] P.-H. Chua, C.-M. S. See, and A. Nehorai, "Vector-Sensor Array Processing for Estimating Angles and Times of Arrival of Multipath Communication Signals," *IEEE Int. Conf. Acoust., Speech, Signal Processing,* pp. 3325-3328, Seattle, WA, May 1998.

[11] A. Nehorai and P. Tichavský, "Cross-Product Algorithms for Source Tracking Using an EM Vector Sensor," *IEEE Int. Conf. Acoust., Speech, Signal Processing,* pp. 2781-2784 Phoenix, AZ, March 1999.

[12] A. Nehorai and P. Tichavský, "Cross-Product Algorithms for Source Tracking Using an EM Vector Sensor," *IEEE Trans. on Signal Processing* Vol. SP-47, pp. 2863-2867, Oct., 1999.

[13] C-M. See and A. Nehorai, "Distributed Electromagnetic Component Sensor Array Processing," *Proc. 7th Workshop on Adaptive Sensor Array Processing,* pp. 75-79, Lincoln Laboratory, MIT, Boston, MA, March 1999. (Invited.)

[14] C-M. See and A. Nehorai, "Source localization with distributed electromagnetic component sensor array processing," *Proc. 2nd Joint USA/Australia Workshop in Defense Applications of Signal Processing,* pp. 161-166, LaSalle, IL, Aug. 1999. (Invited.)

[15] A. Dogandžić and A. Nehorai, "Cramér-Rao bounds for estimating range, velocity, and direction with a sensor array," to appear in *Proc. 1st IEEE Sensor Array and Multichannel Signal Processing Workshop (SAM 2000),* Cambridge, MA, March 2000.

[16] A. Dogandžić and A. Nehorai, "Cramér-Rao bounds for estimating range, velocity, and direction with a sensor array," in revision for *IEEE Trans. on Signal Processing.*

[17] A. Dogandžić and A. Nehorai, "Estimating Range, Velocity, and Direction with a Radar Array," *IEEE Int. Conf. Acoust., Speech, Signal Processing,* pp. 2773-2776, Phoenix, AZ, March 1999.

[18] C-M. See, A. Nehorai, and C. F. N. Collins, "Spatio-Temporal Channel Identification and Equalization in the Presence of Strong Co-Channel Interference," in *Proc. 32nd Asilomar Conf. Signals, Syst. Comput.,* pp. 1101-1105, Pacific Grove, CA, Nov. 1998. (Invited.)

[19] C-M. See, C. F. N. Collins, and A. Nehorai, "Spatio-Temporal Channel Identification and Equalization in the Presence of Strong Co-Channel Interference," *Signal Processing,* pp. 127-138, Vol. 78, Issue 2, 1999.

[20] C.-M. S. See and A. Nehorai, "Estimating Directions and Times of Arrival of Multipath Signals Using a Calibrated Space-Time Antenna Array," *Proc. 9th IEEE SP Workshop on Statistical Signal and Array Processing*, pp. 364-367, Portland, OR, Sept. 1998.

[21] A. Dogandžić and A. Nehorai, "Space-time fading channel estimation in unknown spatially correlated noise," *Proc. 37th Annu. Allerton Conference Commun., Control, and Computing,* Monticello, IL, Sept. 1999, pp. 948–957.

[22] A. Dogandžić and A. Nehorai, "Space-time fading channel estimation and symbol detection in unknown spatially correlated noise," submitted to *IEEE Trans. on Signal Processing.*

[23] N. Zou and A. Nehorai, "Detection of Ship Wake Using an Airborne Magnetic Transducer," in *Proc. 32nd Asilomar Conf. Signals, Syst. Comput.*, pp. 1316-1320, Pacific Grove, CA, Nov. 1998. (Invited.)

[24] N. Zou and A. Nehorai, "Detection of ship wakes using an airborne magnetic transducer," *IEEE Trans. on Geoscience and Remote Sensing*, pp. 532-539, Vol. 38, Jan. 2000.

[25] M. Hawkes and A. Nehorai, "Acoustic vector-sensor beamforming and Capon direction estimation," *IEEE Trans. Signal Processing*, vol. 46, pp. 2291–2304, Sept. 1998.

[26] M. Hawkes and A. Nehorai, "Effects of sensor placement on acoustic vector-sensor array performance," *IEEE Jour. of Oceanic Eng.*, vol. 24, no. 1, pp. 33-40 Sept. 1998.

[27] M. Hawkes and A. Nehorai, "Acoustic vector-sensor processing in the presence of a reflecting boundary," to appear in *IEEE Trans. Signal Processing,* Vol. 48, Nov. 2000.

[28] M. Hawkes and A. Nehorai, "Acoustic vector-sensor correlations in ambient noise," submitted to *IEEE J. Oceanic Eng.*

[29] M. Hawkes and A. Nehorai, "Battlefield Target Localization Using Acoustic Vector Sensors and Distributed Processing," *Proc. 1999 Meeting of the IRIS Specialty Group on Battlefield Acoustics* (Invited), pp.111-128, Laurel, MD, Sept. 1999.

[30] M. Hawkes and A. Nehorai, "Distributed processing for 3-D localization using acoustic vector sensors on the seabed or battlefield," *Proc. 8th Ann. Adapt. Sensor Array Process. Workshop (ASAP2000)*, Lexington, MA, Mar. 2000.

[31] M. Hawkes and A. Nehorai, "3-D localization using a distributed array of acoustic vector sensors" in preparation.

[32] M. Hawkes, "Issues in Acoustic Vector-Sensor Processing," Ph.D. Thesis, Department of Electrical Engineering, Yale University, CT, September 2000.

[33] F-L. Luo, J. Yang, C. Pavlovic, and A. Nehorai, "An FFT based algorithm for adaptive directionality of dual microphones," submitted for publication.

[34] A. Jeremić and A. Nehorai, "Design of Chemical Sensor Arrays for Monitoring Disposal Sites on the Ocean Floor," *IEEE Int. Conf. Acoust., Speech, Signal Processing,* pp. 2013-2016, Seattle, WA, May 1998.

[35] A. Jeremić and A. Nehorai, "Design of Chemical Sensor Arrays for Monitoring Disposal Sites on the Ocean Floor," *IEEE Journal of Oceanic Engineering,* Vol. 23, pp. 334-343, Oct. 1998.

[36] A. Jeremić and A. Nehorai, "Mine detection and localization using chemical sensor array processing," *Proc. SPIE on Detection and Remediation Technologies for Mines and Minelike Targets IV,* pp. 380-391, Orlando, FL, April 1999.

[37] A. Jeremić and A. Nehorai, "Mine detection and localization using chemical sensor array processing," *IEEE Trans. on Signal Processing,* pp. 1295-1305, Vol. SP-48, May 2000.

[38] A. Dogandžić and A. Nehorai, "Estimating Evoked Dipole Responses by MEG/EEG for Unknown Noise Covariance," *Proc. 19th Annu. Int. Conf. IEEE Eng. Med. Biol. Soc.,* pp. 1224–1227, Chicago, IL, Oct. 1997.

[39] A. Dogandžić and A. Nehorai, "EEG/MEG spatio-temporal dipole source estimation," to appear in *Proc. 31st ISCIE International Symposium on Stochastic Systems Theory and Its Applications*, pp. 1-6, Keio University, Japan, Nov. 1999. (Invited.)

[40] A. Dogandžić and A. Nehorai, "Estimating Evoked Dipole Responses in Unknown Spatially Correlated Noise with EEG/MEG Arrays," *IEEE Trans. on Signal Processing,* pp. 13-25, Vol. SP-48, Jan. 2000.

[41] A. Dogandžić and A. Nehorai, "Localization of Evoked Electric Sources and Design of EEG/MEG Sensor Arrays," *Proc. 9th IEEE SP Workshop on Statistical Signal and Array Processing*, pp. 228-231, Portland, OR, Sept. 1998.

[42] A. Nehorai and A. Dogandžić, "Estimation of Propagating Dipole Sources by EEG/MEG Sensor Arrays, in *Proc. 32nd Asilomar Conf. Signals, Syst. Comput.*, pp. 304–308, Pacific Grove, CA, Nov. 1998. (Invited.)

[43] C. Muravchik and A. Nehorai, "MEG/EEG Numerical Error Bounds for a Dipole Source with a Realistic Head Model," *Proc. 19th Annu. Int. Conf. IEEE Eng. Med. Biol. Soc.*, pp. 1233-1236, Chicago, IL, Oct. 1997.

[44] C. Muravchik and A. Nehorai, "Error bounds of EEG/MEG for a stationary dipole source with a realistic head model," *IEEE Int. Conf. Acoust., Speech, Signal Processing,* Istanbul, Turkey, June 2000. (Invited.)

[45] C. Muravchik and A. Nehorai, "EEG/MEG numerical error bounds for a dipole source with a realistic head model," to appear in *IEEE Trans. Signal Processing.*

[46] O. Bria, C. Muravchik, and A. Nehorai "EEG/MEG error bounds for a dynamic dipole source with a realistic head model," *Proc. 3rd Int. Workshop on Biosignal Interpretation,* pp. 75-78, Chicago, IL, June 1999.

[47] C. Muravchik, O. Bria, and A. Nehorai, "EEG/MEG error bounds for a dynamic dipole source with a realistic head model," *Methods of Information in Medicine*, pp. 110-113, Vol. 39, No. 2, 2000.

[48] A. Nehorai and A. Jeremic, "Estimating Mechanical Properties of the Left Ventricle Using Dynamic Modeling and Magnetic Resonance Imaging," in *Proc. Computers in Cardiology '98*, Cleveland, OH, pp. 257-260, Sept. 1998.

[49] A. Jeremic and A. Nehorai, "Estimating Mechanical Properties of the Heart Using Dynamic Modeling and Magnetic Resonance Imaging," *IEEE Int. Conf. Acoust., Speech, Signal Processing,* Istanbul, Turkey, June 2000. (Invited.)